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HEATING REMOTE ROOMS IN PASSIVE SOLAR BUILDINGS*

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ABSTRACT

Remote rooms can be effectively heated by convection through a connecting doorway. A simple steady-state equation is developed for design purposes. Validation of a dynamic model is achieved using data obtained over a 13-day period. Dynamic effects are investigated using a simulation analysis for three different cases of driving temperature; the effect is to reduce the temperature difference between the driving room and the remote room compared to the steady-state model. For large temperature swings in the driving room a strategy which uses the intervening door in a diode mode is effective. The importance of heat-storing mass in the remote room is investigated.

KEY WORDS

Natural convection; passive solar heating; building thermal analysis; performance evaluation; model validation.

INTRODUCTION

Many of the original passive solar buildings are either one-room deep or rely primarily on backup systems for the heating of rooms which are remote from the source of solar heat, for example, rooms on the north side of a building. Many designers have solved this problem in single-story structures by the use of clerestory roof monitors which allow the sun to shine directly on the inside of the north wall. Where applicable, this scheme works well. However, in multi-story and many other building configurations there are inevitably rooms which are remote from the source and cannot be heated in this fashion. Some elaborate schemes utilizing ducted hot air have been devised. However, simple convection of heat through open doorways from south rooms to north rooms appears to be a very effective mechanism for heat exchange in many situations.

DOORWAY CONVECTION EQUATION

Convection of air through a doorway which connects two adjacent spaces has been discussed by Wray (1979) and Weber (1979). Further experimental work is described by Weber and Kearney (1980) who conclude with a recommendation for a

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correlation equation between Nusselt number (Nu), Prandtl number (Pr), and Grashof number (Gr) as follows:

$$Nu/Pr = 0.3\ Gr^{1/2} \qquad (1)$$

The ΔT to be used in this equation is the temperature difference between the average temperature in the two adjacent rooms. The coefficient in this equation may be somewhat geometry dependent; further experimental work is in progress to study this question. We will assume that air temperature measurements made 1.5 m (4.9 ft) above the floor will suffice for describing the room temperatures. Introducing the properties of air, we obtained the following convenient working equations. In SI units the heat flow Q (watts) is as follows:

$$Q = 63.5\ w\ (h\Delta T)^{3/2};\ w = \text{door width (m)},\ h = \text{door height (m)},\ \Delta T \text{ in } ^oC \qquad (2)$$

In traditional British units Q is in Btu/hr and the equation is:

$$Q = 4.6\ w\ (h\Delta T)^{3/2};\ w = \text{door width (ft)},\ h = \text{door height (ft)},\ \Delta T \text{ in } ^oF \qquad (2)$$

STEADY-STATE SOLUTION

Consider the simple case of a room which is heated only by convection through a doorway from an adjacent space at a steady temperature and which loses heat to a steady outside temperature through a fixed loss coefficient. In this case the solution is very simple. The energy balance equation is as follows:

$$Q = 63.5\ w(h(Td-Tr))^{3/2} = LC\ (Tr-Ta) \qquad (3)$$

LC = loss coefficient, w/C; Td = driving temp.,
Ta = ambient temp.; Tr = room temp, C.

The solution to this equation gives the room-to-room temperature difference as a function of the room-to-outside temperature difference for different values of the Load-Door Ratio (LDR).

$$\Delta T = Td - Tr = ((LDR\ (Tr-Ta)/63.5)^2/h)^{1/3} \qquad (4)$$

LDR = LC/(wh), (in British units 63.5 becomes 4.6)

If the door height is specified, then the equation can be represented graphically as shown in Fig. 1. This graph can be used as a design aid for determining the necessary door size for a particular given inside-outside temperature difference. Equation 4 is not very sensitive to door height.

POWDER ROOM EXPERIMENT

The powder room is a small remote bathroom on the ground floor at the north side of the Balcomb solar home. It has a single doorway, which is nearly always open. The east and west walls and ceiling are of wood frame construction and connect to adjacent spaces at nearly the same temperature. The north wall represents the only heat load and contains a single, double-glazed window. The floor is concrete.

The central question is whether or not temperatures observed in the powder room can be rationalized based on convection through the doorway. A test period was chosen when there was no source of heat other than solar. Temperatures in the adjacent living room area were strongly solar driven by a complex series of mechanisms involving convection from the adjacent attached sunspace, conduction through the mass wall adjacent to the sunspace, and a small amount of direct solar gain.

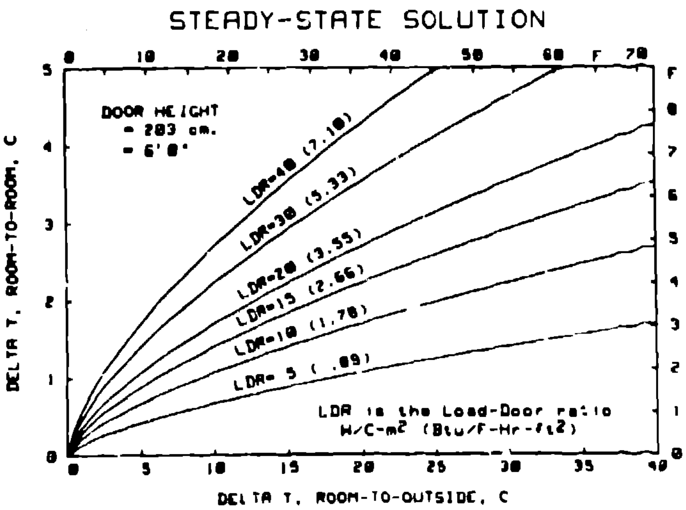

Fig. 1. Graphical representation of Eqn. 4.

<u>Powder Room Model</u>

The mathematical model of the room was deliberately made simple. Four energy flows were considered. The first is convection through the doorway, the second is direct heat flow to the outside temperature (both by conduction and infiltration), and the last two deal with heat storage in the plaster walls and other elements of the room, including the wood-beamed ceiling and other furnishings. These latter two were treated as simple resistance-capacitance connections to the room air.

The loss coefficient from the room to the outside is 5.71 watts/C (10.8 Btu/hr-F), calculated using conventional steady-state heat flow relationships. The door is 203 cm (6.67 ft) high by 61 cm (2 ft) wide for a total area of 1.24 m^2 (13.2 ft^2). The Load-Door Ratio (LDR) is the ratio of the heat loss coefficient to the door area and is 4.6 W/m^2-C (0.82 Btu/hr-F-ft^2). The total mass heat capacity is 694 Whr/C(1317 Btu/F) and the total mass surface is 24.1 m^2 (259 ft^2).

The mathematical model was solved hourly in order to find a room temperature which would satisfy an overall heat balance equation considering the four energy flows discussed above. The independent variables are the adjacent living room temperature and the outside air temperature. The results are shown in Fig. 2 which compares the predicted and measured room temperature for a 13-day interval. The root-mean-square error between the measurement and prediction is 0.3 C. The average temperature difference between the powder room and the outside is 17 C (30 F) and the average temperature difference between the living room and the powder room is 0.9 C (1.6 F). The predicted ΔT based on Eqn. 4 is also 0.9 C.

SIMULATION RESULTS

How good is Eqn. 4 or Fig. 1 in predicting other situations? How important are the dynamics and the non-linearities? In order to answer these questions a series of 180-day simulations were made with representative data for a driving temperature. It was felt that room temperatures from passive solar buildings should be used. Three different temperatures traces were obtained, each for an entire 180-day heating season. These will be subsequently referred to as Case A, Case B, and Case C. Case A has the least variation and Case C the greatest variation.

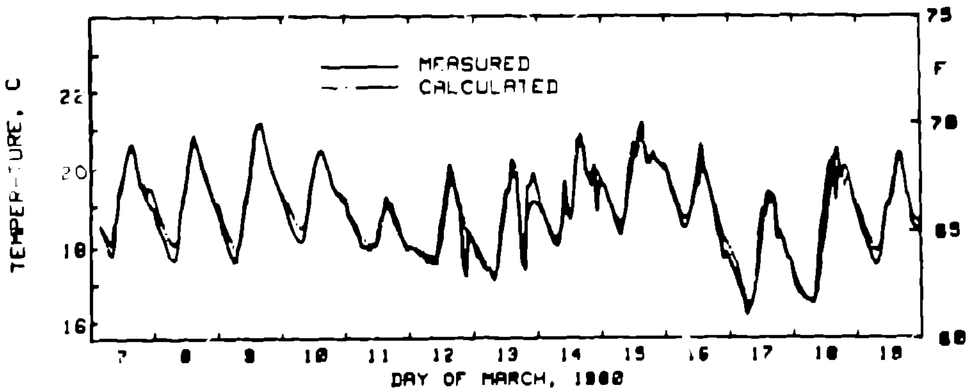

Fig. 2. Comparison of measured and calculated temperature in the Balcomb house powder room.

Case A uses the result of the simulation of a passive solar home outside of Denver, Colorado. The house is quite massive and is solar heated by a combination of direct gain and Trombe wall. Because of the large mass, temperature swings in the room temperature are quite small, averaging 1.4 C (2.6 F) over the heating season with peak daily temperature swings of 3.3 C (6 F). Cases B and C use actual data taken in the Balcomb solar home over the winter of 1978-79. Case B uses temperatures taken in the living room which has an average temperature swing of 3.1 C (5.6 F) with maximum swings of 5 C (9 F). Case C uses the temperature measured in the two-story attached sunspace. This is a very strongly heated direct gain space. The average temperature swing is 14.5 C (26.1 F) and typical peak swings are 19 C (35 F).

The powder room mathematical model was used with each of these three cases of driving temperature. The outside temperature was taken from the data and the simulation was made using a one-hour time step through the entire heating season. The results of the first study are shown in Table 1. For each case there were two different values of Load-Door Ratio (LDR) used, one corresponding to the powder room in the Balcomb house and a second with five times the load and also five times the storage heat capacity. In this table ΔT refers to the average temperature difference between the driving temperature and the remote room averaged over the heating season and ΔT_{ss} is a steady-state calculation using Eqn. 4 in which the room-to-outside temperature difference is the average for the heating season. From Table 1 one can see that the steady-state equation always seems to overpredict the calculation based on the dynamic model. This is expected considering the type of non-linearity in Eqn. 4. The overprediction is quite small in Cases A and B, in which the temperature variations of the driving temperature are small, but is significant for Case C where the swings in driving temperature are huge.

TABLE 1 -Simulation Results vs Steady-State Prediction

Case	LDR*	ΔT*	ΔT_{ss}*	ΔT swing*
A	4.6 (0.82)	0.86 (1.55)	0.88 (1.59)	1.1 (2.0)
A	23 (4.1)	2.38 (4.28)	2.42 (4.35)	0.9 (1.7)
B	4.6 (0.82)	0.89 (1.61)	0.95 (1.71)	2.1 (3.7)
B	23 (4.1)	2.54 (4.57)	2.61 (4.70)	1.4 (2.5)
C	4.6 (0.82)	0.26 (.47)	0.91 (1.64)	9.6 (17.2)
C	23 (4.1)	1.39 (2.51)	2.55 (4.59)	5.2 (9.4)

*SI units (British units in parenthesis)

The results of a second study are shown in Table 2. The object was to investigate the effectiveness of "diode door control." In this case the doorway connecting the driving room with the remote room is closed when the temperature in the driving room is below the remote room. This allows one to convect heat into the remote room during the day and prevent its return at night. This strategy is only of interest if the temperature swings in the driving room are quite large large and thus only Case C was studied.

TABLE 2 Effect of Diode Door Control (Case C, LDR = 23 (4.1)

	ΔT, C (F)
Door always open	1.39 (2.51)
Diode door control	0.58 (1.05)

TABLE 3 Effect of Room Heat Storage Mass (Case C, LDR = 23 (4.1), diode door)

Mass	ΔT	ΔT swing
base case	0.58 (1.05)	4.5 (8.1)
2 x base case	-0.11 (-.19)	2.6 (4.7)
base case/2	1.47 (2.64)	7.3 (13.1)

The third study concerned the effect of room heat storage mass on the results. The "base case" is the same as the powder room except the LDR was increased by using a load five times the powder room load. The area and mass of heat storage was also increased by five times. The simulation was then run again with the mass and mass surface area each reduced by two times and then increased by two times. The results are shown in Table 3. The mass clearly has an effect on both the average temperature difference between the rooms and on the temperature swing in the remote room. In one instance the average temperature in the remote room is actually higher than the driving room due to the diode effect and the ability of the room to carry over heat from the day into the night. This is indicated by the minus sign. The temperature swings in the low-mass case are marginal and in the high-mass case are probably acceptable.

CONCLUSIONS

1. Convection through doorways is a very effective way of heating remote rooms. Quite reasonable temperature differences between the driving room and the remote room can be maintained.
2. The steady-state solution given in Eqn. 4 or Fig. 1 gives good indication of the temperature differences which can be expected under most conditions.
3. The effect of large variations in the driving temperature is advantageous, generally decreasing the difference between the average temperature in the driving room and in the remote room. Temperature swings in the remote room are always less than the driving room.
4. If the temperature swing in the driving room is quite large, as in the case of an attached sunspace, then a diode door strategy can improve the situation, decreasing the ΔT.
5. Heat storage in the remote room is quite important if the driving temperature swing is large. Insufficient mass will lead to excessive temperature swings.

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